A COMPARISON OF THE EFFECT OF WATER ON THE BONDING STRENGTHS OF TREATED AND UNTREATED BITUMINOUS MIXTURES

SYED AHMAD FARHAN BIN SYED AHMAD ISKANDAR

CIVIL ENGINEERING
UNIVERSITI TEKNOLOGI PETRONAS
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by

Syed Ahmad Farhan bin Syed Ahmad Iskandar

Thesis submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

(Assoc. Prof. Dr. Ibrahim bin Kamarudin)
Main Supervisor

Assoc. Prof Ir. Dr. Ibrahim bin Kamaruddin

Universiti Teknologi PETRONAS
Tronoh, Perak
July 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

SYED AHMAD FARHAN BIN SYED AHMAD ISKANDAR

ABSTRACT

The performance of the nation's highways highly affects the nation's economy. The performance of roads and highways are inter-related with various economic activities. The deterioration of pavement materials will lead to high maintenance costs. The challenging conditions that pavement materials are exposed to in Malaysia demands more research in this field of civil engineering.

In recent years, research in this area has focused more on the methods of treating paving mixtures. This study is focused on the bituminous mixtures. The purpose of this study is to see the correlation between the effects of water and the treatment methods on bituminous mixtures.

Marshall Properties Test was conducted on five (5) samples with binder contents of 4.5%, 5%, 5.5%, 6% and 6.5% to obtain the Optimum Bitumen Content (OBC). The OBC obtained was 5.21%. Three (3) samples with the same binder contents of 5.21%, and varying filler compositions of 4% Ordinary Portland Cement (OPC), 2% OPC and 2% Hydrated Lime (HL) and 4% HL were prepared. Moisture Susceptibility Test was conducted on those samples to see how water affects the Marshall Properties of each sample. The Immersion Index for each sample was determined to see how the varying filler composition affects the resistance of each sample towards the effect of water.

Data obtained showed that water caused a decrease in stability and stiffness, and an increase in flow. However, samples with 4% HL showed the greatest resistance to the effect of water, followed by samples with 2% OPC and 2% HL.

It can be concluded from this study that the resistance of bituminous mixtures with the HL filler is better than that containing OPC filler.

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LIST OF ABBREVIATIONS

ACW	Asphaltic Concrete Wearing
ASTM	American Society of Testing Materials
BS	British Standards
HL	Hydrated Lime
II	Immersion Index
JKR	Jabatan Kerja Raya
OBC	Optimum Bitumen Content
OPC	Ordinary Portland Cement
VFB	Voids Filled with Bitumen
VTM	Voids in Total Mix

CHAPTER 1
INTRODUCTION

1.1 Background

Malaysia's road system is extensive and is among the finest in Asia. It covers a distance of 63,445 km. The total number of vehicles, registered at the end of 1990 was about 5.2 million. Improvements in road infrastructure and extensive road network coupled with increases in population and income levels had resulted in an increase in the ownership of motor vehicles. In 1993, there were 5.4 million motor vehicles of which 38.6% were motorcars, 54.8% motorcycles and 6.6% goods vehicles. This increased by 50.5% to reach 8.1 million motor vehicles in 1997, with motorcycles accounting for 53% of the total, followed by motorcars 40% and goods vehicles 7%. The number of motor vehicles per 100 persons, which is an indicator of the quality of life of the population, increased from 27.6 in 1993 to 37.6 in 1997. [1]

Malaysia has an equatorial climate, giving it a warm and wet weather due to its proximity to the equator. Temperatures in the lowlands range between 29°C - 35°C during the day and 26°C - 29°C at night, depending on the amount of rainfall and sunlight. On an average, Malaysia receives about 6 hours of sunshine each day with cloud formations occasionally leading to rainfall. There are two monsoon winds that influence the rainfall at different intervals of the year. The Southwest Monsoon usually occurs between May till September, bringing rainfall to the western side of Peninsular Malaysia. On the other hand, the Northeast Monsoon starts from November and lasts till March, brining heavy rainfall to areas on the east side of Peninsular Malaysia, such as Kuantan, and Borneo (Sabah and Sarawak). As this monsoon wind is particularly strong, it often brings heavy rain to the west side of Peninsular Malaysia as well during this period. However, the daytime is usually warm and sunny, with heavy rains only occurring in the evenings onward. [2]

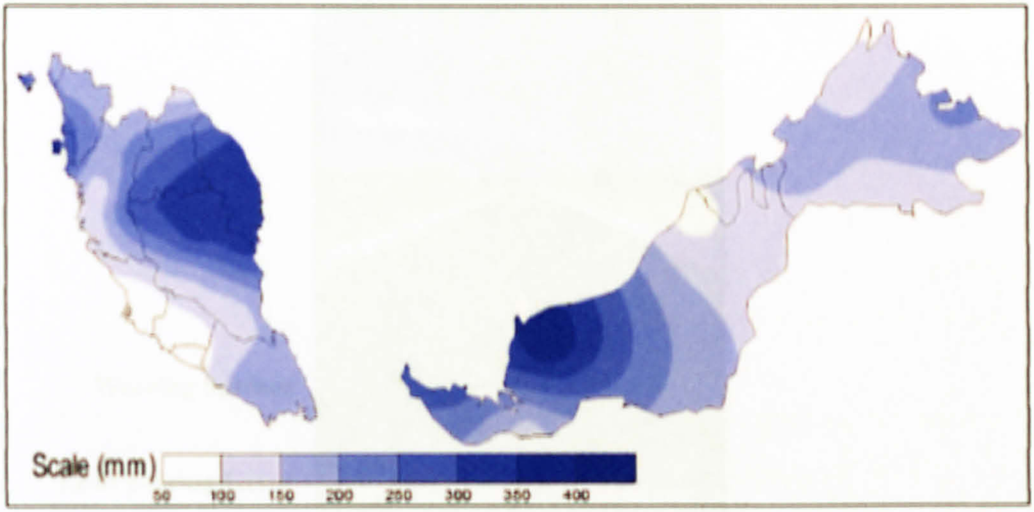

Figure 1.1: Total Rainfall in Malaysia for the Month of May 2009

Rainfall affects the performance of asphalt pavements. The constant intrusion of water on and into the asphalt pavements can cause accelerated weakening of roads throughout the country, hence decreasing the lifespan of the nation's highways.

1.2 Problem Statement

Bitumen is a viscous liquid or solid, black or brown in colour and has adhesive properties. It is a mixture of natural pyrogenous hydrocarbons and their non-metallic derivatives. Bitumen is usually derived from petroleum crude by a distillation process.

A typical pavement consists of several layers. Two of the most important layers are the top two layers; the wearing surface and intermediate, load bearing layer. Both of these layers utilize asphalt binder to bind aggregate together for a mixture that sustains applied loads and maintains durability.

Figure 1.2: Layers of Asphalt Pavement

Moisture is the major environmental condition that adversely affects asphalt concrete quality and primarily results in bond strength degradation. Moisture damage is caused by distress mechanisms induced by the presence or infiltration of moisture and manifests itself in a phenomenon referred to as stripping, where the asphalt binder is stripped from the aggregate.

In order to withstand increasing traffic loads and the effects that come with the challenging environmental conditions, it is important that research on bitumen modification and treatment is conducted to come out with new methods of increasing the performance of the nation's asphalt pavements under the presence of water.

1.3 Objectives

Aims of this study are as follows:

1) To study the effects of water on the Marshall Properties of Bituminous Mix Design ACW14.
2) To study the effectiveness of Ordinary Portland Cement (OPC) in reducing the effects of water on the Marshall Properties of Bituminous Mix Design ACW14.
3) To study the effectiveness of Hydrated Lime (HL) in reducing the effects of water on the Marshall Properties of Bituminous Mix Design ACW14.
4) To make comparison between the effectiveness of OPC and HL as additives for prevention of water damage in Bituminous Mix Design ACW14.

1.4 Scope of Study

The scope of this study is summarized as the following:

1) Preparation of untreated and treated samples of Bituminous Mix Design ACW14.
2) Implementation of Penetration Test and Softening Point Test for Bitumen Testing.
3) Implementation of Specific Gravity Test for determination of Water Absorption for both fine and coarse aggregates.
4) Implementation of Marshall Properties Test for determination of Optimum Bitumen Content.
5) Implementation of Moisture Susceptibility Test.
6) Determination of Immersion Index for data comparison and analysis.

CHAPTER 2
LITERATURE REVIEW

2.1 Treatment Methods

The bonding between asphalt and aggregate is a primary characteristic that influences the integrity of the pavement. Loss of bonding results in lowered performance. There are three characteristics which contribute towards pavement strength [3]:

1. Cohesive resistance of the binder
2. Adhesive bond between the binder and the aggregate
3. Aggregate interlock and the frictional resistance between aggregate particles

A number of different methods have been used to strengthen the adhesion of asphalt to aggregate and to lower the pavement's propensity to strip from the intrusion of moisture. Below are some of the methods that have been used [3]:

1. Addition of dry lime, hydrated lime or ordinary Portland cement to the mix as fillers
2. Lime-slurry treatment of the aggregates
3. Bitumen precoating of the aggregates
4. Careful selection of aggregates using special mineral fillers or not allowing hydrophilic aggregates
5. Washing or blending of aggregates
6. Addition of chemical anti-stripping agents

2.2 Filler Types

Fillers can be used as additive material in bituminous mixtures to improve the performance of pavement and to minimize distress due to traffic loading and environmental conditions. For this research, two types of fillers are used, which are hydrated lime and ordinary Portland cement (OPC). It is expected that the incorporation of these fillers into the mix will reduce damage to specimen due to intrusion of moisture.

2.2.1 Hydrated Lime

Hydrated lime ($Ca(OH)_2$) is produced from the heating of limestone or calcium carbonate to remove carbon dioxide. The residual calcium oxides are also known as quicklime. A controlled amount of water is added to form calcium hydroxide to improve the handling characteristics of quicklime. This combination of quicklime and water is referred to as hydrated lime.

Below is the equation for the chemical reaction between quicklime (CaO) and water (H_2O), which produces hydrated lime ($Ca(OH)_2$) and generates heat:

Calcium Oxide + Water = Calcium Hydroxide + Heat

$$\{CaO\} + \{H_2O\} = \{Ca(OH)_2\}$$

Addition of lime constituent to the aggregate carries an intention to improve the bond between the aggregate and bitumen. Hydrated lime is a combination of lime and water. Previous studies have shown that additions of the modest amount of commercial hydrated lime (0.5% - 2% by weight) are one of the most recognized ways to prevent anti-stripping of bituminous paving mixtures.

Table 2.1: Chemical Properties of Hydrated Lime [4]

IUPAC Name	*Calcium Hydroxide*
CAS Number	*1305-62-0*
Molecular Formula	$Ca(OH)_2$
Molar Mass	*74.093 g/mol*
Grading	*50% less than 0.005 mm*
Appearance	*Soft white powder or colourless liquid*
Density	*2.211* g/cm^3 *(solid)*
Melting Point	512^oC
Solubility in Water	*0.185 g / 100* cm^3
Solubility Equilibrium	7.9×10^{-6}
Basicity	*- 2.37*
pH	*12.0 – 12.5*

Hydrated lime has the ability to control water sensitivity and to act as an anti-stripping agent to inhibit moisture damage. Lime acts as an active filler, anti-oxidant and as an additive in bituminous mixtures. These mechanisms create several benefits for pavements [5]:

1. It acts as mineral filler, stiffening the asphalt binder.
2. It improves resistance to fracture growth at low temperatures.
3. It favorably alters oxidation kinetics and interacts with products of oxidation to reduce their deleterious effects.
4. It alters the plastic properties of clay fines to improve moisture stability and durability.
5. It reduces the potential of asphalt to deform at high temperatures, especially during its early life when it most susceptible to rutting.

2.2.2 Ordinary Portland Cement (OPC)

Portland cement is the most common type of cement in general use around the world, because it is a basic ingredient in concrete, mortar, stucco and most non-specialty grout. It is a fine powder produced by grinding Portland cement clinker (more than 90%), a limited amount of calcium sulfate which controls the set time, and up to 5% minor constituents (as allowed by various standards). [6]

Table 2.2: Typical Constituents of OPC [6]

Compound	*Percent by Mass (%)*
Calcium Oxide (CaO)	61 – 67
Silicon Oxide (SiO_2)	19 - 23
Aluminium Oxide (Al_2O_3)	2.5 - 6
Ferric Oxide (Fe_2O_3)	0 - 6
Sulfate	1.5 – 4.5

OPC is derived from the combustion of limestone and clay at a very high temperature, in the range of 1400 – 1600°C. It can be used as mineral filler with asphalt binder in flexible pavement. Due to its fine particle size, it can fill the voids in aggregates, resulting in a viscous mastic system. The principal constituents of OPC are compounds of lime, iron, silica and alumina. With these compositions, bituminous mixtures containing OPC is found to be more resistant to stripping. [7]

Incorporation of OPC into bitumen was found to result in a low consistency binder with higher penetration, lower softening point temperature and viscosity compared to other fillers such as hydrated lime, fly ash, limestone and silt. [8]

2.3 Distress Mechanisms in Highways

2.3.1 Stripping and Raveling

Stripping in asphalt pavements is defined as the displacement of asphalt cement film from aggregate surfaces by water. Stripping that occurs on the surface of a pavement is referred to as raveling. Raveling is the wearing away of the asphalt pavement surface caused by the dislodging of aggregates due to stripping.

Figure 2.1: Stripping at Bottom of Hole

Stripping can occur due to many causes including improper material selection, poor mixture design and construction, and the presence of water in the mixture or pavement layers.

There are five primary mechanisms that either act individually or together to cause the debonding of asphalt from aggregate, followed by stripping of asphalt pavements. The mechanisms are [9]:

1. Detachment, which is the separation caused by water of the asphalt film from the aggregate without any visual break in the asphalt film.
2. Displacement, which results from the intrusion of water to the aggregate surface through a break in the asphalt film or through the film itself.
3. Spontaneous emulsion, which is the formation of a inverted reversible emulsion at the aggregate.

4. Pore pressure, which is the increased pressure caused by circulation of trapped water through the void structure of the aggregate.
5. Hydraulic scouring, which occurs on surface courses because of a compression tension cycle caused by the interaction of tire pressure with surface water.

2.3.2 Fatigue Cracking

Fatigue cracking is considered a major structural distress of pavements and is a load-associated distress mechanism. Fatigue cracking is a chain of interconnected cracks caused by failure of asphalt surface or stabilized base under cyclic traffic loading. "Bottom-up" cracking begins at the bottom of the asphalt surface where the tensile stress or strain is highest under the wheel load. The cracking then propagates upwards toward the surface where longitudinal cracks appear. Longitudinal cracks run parallel to the pavement's centerline and are indicative of the beginning of fatigue cracking. Due to repetitive loading the cracks connect and develop a pattern that resembles the skin pattern on an alligator and is termed "alligator cracking". In the case of thick pavements, the cracks may propagate at the surface and migrate downwards which is referred to as "top-down" cracking. Excessive or severe alligator cracking can lead to potholes. Potholes occur when there is a hole left after interconnected cracks create a small piece of pavement that is broken from the pavement surface. Potholes may also be formed during freeze-thaw cycling or localized disintegration within the bituminous pavement layer.

Figure 2.2: Pothole from Fatigue Cracking

Fatigue cracking occurs due to a loss of structural support. Moisture has an effect on the structure of the pavement in two possible locations: at the subgrade or base layers and within the compacted bituminous layer. The subgrade or base layers can lose support due to poor drainage and during the thawing process. Stripping may occur as a result of high tensile stresses in the bottom of the bituminous layer. The stripped area will not provide any support so the effective compacted bituminous layer thickness is decreased. Further, fatigue cracking allows moisture infiltration, which can lead to further damage and the onset of other distress mechanisms.

2.3.3 Thermal Cracking

Thermal cracking is not associated with loading and occurs due to low temperature shrinkage or hardening of the compacted bituminous mixture. The change in temperature results in cyclic stresses and strains that cause longitudinal and transverse cracking at the asphalt surface. Transverse cracks are perpendicular to the pavement's centerline. Changes in the moisture state in an asphalt mixture have a significant impact on low-temperature properties of the asphalt mixtures. Thus, moisture most likely may have an impact on the thermal-cracking performance of asphalt pavement.

Figure 2.3: Thermal Cracking

2.3.4 Permanent Deformation and Rutting

Permanent deformation occurs in the pavement layers or subgrade as a result of consolidation or movement of the materials due to traffic loads. Permanent deformation manifests itself as depressions in the pavement. Rutting is the depression of the surface of the pavement in the wheel paths. Rutting is caused by inadequate compaction (i.e. too low or high air void content) or movement of the pavement layers and can also occur due to plastic flow of asphalt in hot or weakened conditions. Loss of adhesive and cohesive strength within the asphalt mixture due to moisture can facilitate permanent movement under traffic loading.

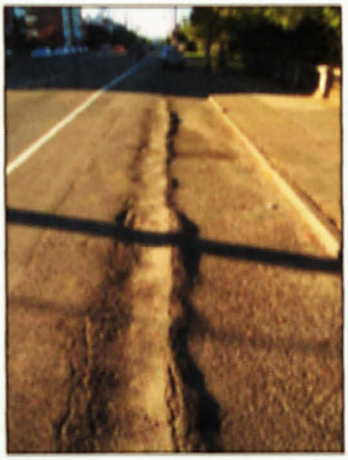

Figure 2.4: Rutting

CHAPTER 3
METHODOLOGY

3.1 Laboratory Analysis Process

The procedure of the laboratory works is illustrated in Figure 3.1.

3.2 Material Preparation

The following are the materials that are used for this research:

Table 3.1: Summary of Materials Used Throughout Research

Material	*Role*
Granite	Coarse Aggregate
Silt/Sand	Fine Aggregate
Ordinary Portland Cement (OPC)	Mineral Filler
Hydrated Lime (HL)	Mineral Filler, Additive
Grade 80/100 Bitumen	Binder

The aggregate gradation for all samples prepared throughout this research is ACW14. Samples are prepared in accordance with the Standard Specification for Road Works published by Jabatan Kerja Raya (JKR) (JKR/SPJ/1988). [10]

Overall, 24 samples were prepared throughout this research. The following table summarizes the types of bituminous samples that were prepared:

Table 3.2: Summary of Samples Prepared Throughout Research

Sample Type Number	Binder Content (%)	Filler Composition (%)	Purpose	Quantity
1	4.5	4% OPC	Determination of Optimum Bitumen Content (OBC)	3
2	5.0	4% OPC		3
3	5.5	4% OPC		3
4	6.0	4% OPC		3
5	6.5	4% OPC		3
6	5.21 (Optimum Binder Content)	4% OPC	Verification of Optimum Bitumen Content (OBC), Moisture Susceptibility Test	3
7	5.21 (Optimum Binder Content)	2% OPC 2% HL	Moisture Susceptibility Test	3
8	5.21 (Optimum Binder Content)	2% OPC 2% HL	Moisture Susceptibility Test	3

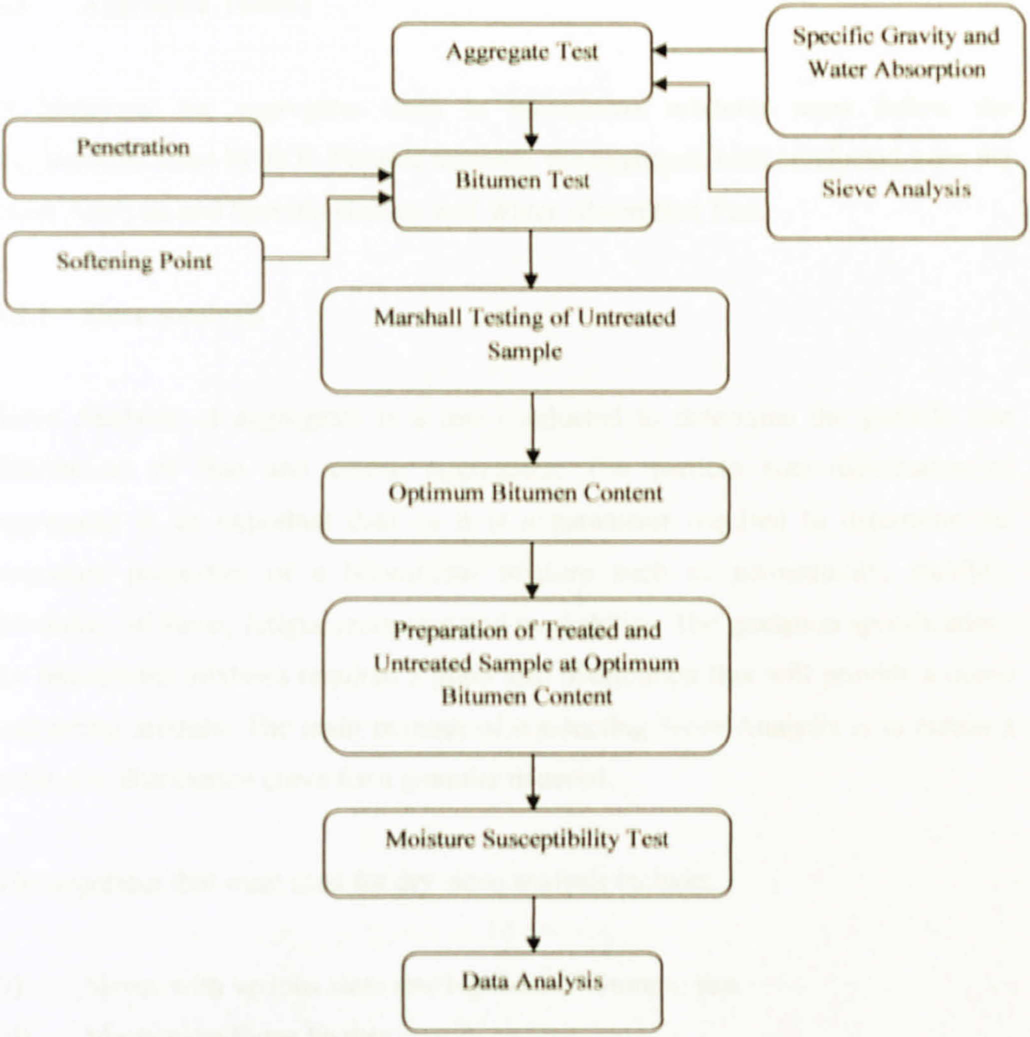

Figure 3.1: Flow Diagram for Laboratory Analysis Process

3.3 Aggregate Testing

In Malaysia, the aggregates used in bituminous mixtures must follow the requirements fixed by JKR. For this research, the aggregate tests conducted were the Sieve Analysis and Specific Gravity and Water Absorption Test.

3.3.1 Sieve Analysis

Sieve Analysis of aggregates is a test conducted to determine the particle size distribution of fine and coarse aggregates. The particle size distribution of aggregates is an important data as it is a parameter required to determine the important properties of a bituminous mixture such as permeability, stability, durability, stiffness, fatigue resistance and workability. The gradation specifications for bituminous mixtures required a grain size distribution that will provide a dense and strong mixture. The main purpose of conducting Sieve Analysis is to obtain a grain size distribution curve for a granular material.

The apparatus that were used for dry sieve analysis include:

(i) Sieves with various sizes starting from 37.5mm to pan
(ii) Mechanical Sieve Shaker
(iii) Balance with the accuracy of 0.5 g

The procedures for dry sieve analysis are as follows:

(i) The sieves were arranged in order of decreasing size of opening from top to bottom on the sieve shaker.
(ii) The aggregate were placed on the top sieve and sieving was started.
(iii) Aggregates that have been sieved were separated according to the size.
(iv) For mixing, total aggregate of different sizes as designed were weighed.

Figure 3.2: Sieve Shaker

3.3.2 Specific Gravity and Water Absorption Test

Specific Gravity Test is a test conducted to measure the density of aggregates in order to determine its specific gravity, which is a measurement of its relative weight to water. Specific Gravity for coarse and fine aggregates was determined separately. Coarse aggregates are the aggregates that are retained on the 4.75mm sieve while fine aggregates are those that passed the 4.75mm sieve.

Coarse Aggregates

The apparatus were used to determine specific gravity are:

(i) Balance, which should be accurate to 0.5 g for the sample weight
(ii) Sample container
(iii)Water tank
(iv)4.75mm sieve size

The procedure for determining specific gravity is as the following:

(i) The aggregates were weighed and washed so that they are clean from dust.

(ii) The aggregates were soaked in water for 24 hours.

(iii) After 24 hours, the aggregates were placed in a basket in water and its weight was recorded while submerged in water for 3 minutes. This mass was recorded as A.

(iv) The aggregates were dried with a damp towel until it was saturated surface dry and is then weighed again. This mass was recorded as B.

(v) The aggregates were dried in an oven for 24 hours at 110 ± 5°C.

(vi) The aggregates were cooled at room temperature and were weighed again. This mass was recorded as C.

(vii) The bulk specific gravity and water absorption of coarse aggregates was calculated using the data recorded above.

Fine Aggregates

The apparatus are:

(i) Pycnometer

(ii) Balance having the capacity of 1 kg with the accuracy of 0.1 g

(iii) Mould in a form of frustum of cone with the following dimension: 40 ± 3mm internal diameter at the top, 50 ± 3mm internal diameter at the bottom and 75 ± 3mm in height

(iv) Tamper weighing 340 ± 15 g having a flat circular face 25 ± 3mm in diameter

The procedures are:

(i) A ¾ filled pycnometer was weighed and recorded as A.

(ii) The water was poured away until the pycnometer is left to about one-quarter filled. About 500 g fine aggregate was added in and shaken well to get rid of air.

(iii) Again, the pycnometer is filled with water until the original level of three-quarters of its volume. The pycnometer was weighed and recorded as B.

(iv) The aggregates were dried in an oven until the aggregate achieve a constant weight. This mass was recorded as C.

(v) The aggregates were mixed with water until the aggregates stuck together. Then, the cone test was performed. If about one-third of the aggregate slumps after 25 light drops of tamper about 5 mm above the top surface of the fine aggregate, the aggregate is saturated surface dry. The weight of saturated surface dry aggregate was weighed and recorded as D.

(vi) Specific gravity and water absorption for fine aggregates was determined using the data recorded above.

3.4 Bitumen Testing

Two of the most common bitumen tests are the Penetration Test and Softening Point Test, both of which indirectly measure the viscosity of a sample of bitumen. The viscosity of a fluid slows down its ability to flow and is a particular significance at high temperature when the ability of the bitumen to be sprayed onto or mixed with aggregate material is of great significance. The results from these two tests enable the engineer to predict the temperature necessary to obtain the fluidity required in the mixture for effect within the pavement.

3.4.1 Penetration Test

Penetration Test gives an empirical measurement of the consistency of a material, indicated by the distance a standard needle sinks into that material under a prescribed loading and time.

The apparatus used were:

(i) Penetration Apparatus

(ii) Needle

(iii) Container

(iv) Water Bath

(v) Thermometer

(vi) Timing Device

(vii) Heater

The procedure to conduct Penetration Test is:

(i) Samples are prepared in containers exactly as specified (ASTM D5-97) and placed in a water bath at the prescribed temperature for 1 to 1.5 hours before the test.

(ii) For normal tests the precisely dimensioned needle, loaded to 100 ± 0.05 g, is brought to the surface of the specimen at right angles, allowed to penetrate the bitumen for 5 ± 0.1 s, while the temperature of the specimen is maintained at 25 ± 0.1 °C. The penetration is measured in PEN (1 PEN = 0.1 mm).

(ii) Make at least three determinations on the specimen. A clean needle is used for each determination. In making repeat determinations, start each with the tip of the needle at least 10 mm from the side of the container and at least 10 mm apart.

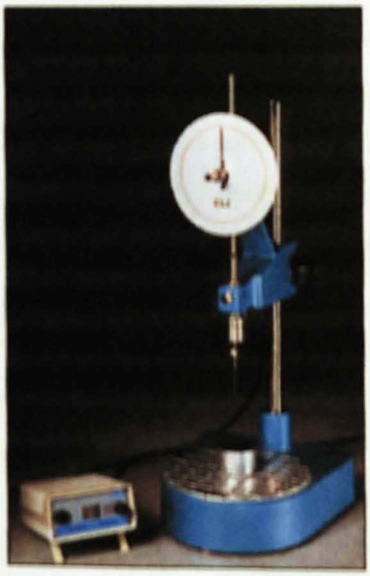

Figure 3.3: Penetrometer

3.4.2 Softening Point Test

The Softening Point Test is used to measure the susceptibility of blown asphalt to temperature changes by determining the temperature at which the material will be adequately softened to allow a standard ball to sink through it.

The apparatus needed are:

(i) Rings
(ii) Base Plate
(iii) Steel balls with 9.5mm in diameter, each weighing 3.50 ± 0.05 g
(iv) Liquid Bath
(v) Ring holder
(vi) Ball guide
(vii) Thermometer

The procedure for conducting Softening Point Test is:

(i) Specimens are prepared in precisely dimensioned brass rings and maintained at a temperature of not less than 10 °C below the expected softening point for at least 30 minutes before the test.
(ii) The rings and assembly, and two ball bearings, are placed in a liquid bath filled to a depth of 105 ± 3 mm and the whole assembly is maintained at a temperature of 5 ± 1 °C for 15 minutes. (Freshly boiled distilled water is used for bitumen with a softening point of 80 °C or below, and glycerine is used for softening point greater than 80 °C).
(iii) A 9.5 mm steel ball bearing (weighing 3.50 ± 0.05 g) is centered on each specimen and heat is then applied to the beaker to raise the temperature by 5 ± 0.5 °C per minute.
(iv) The temperature at which each bitumen specimen touches the base plate is recorded to the nearest 0.2 °C.

Figure 3.4: Apparatus for Softening Point Test

3.5 Marshall Properties Test

To design a bituminous mixture, aggregate types, aggregate gradation and bitumen grade have to be chosen to determine the bitumen content which will optimize the engineering properties in relation to the desired behavior in service. Marshall Mix Design is one method of designing a bituminous mixture. From the Marshall Properties Test, the Optimum Binder Content (OBC) for the bituminous mixture is determined along with its stability and flow.

Figure 3.5: Marshall Test Apparatus

3.6 Moisture Susceptibility Test

The objective of conducting a Moisture Susceptibility Test is to see how the Marshall Properties of bituminous specimens fluctuate due to the effects of water.

The apparatus used were:

(i) Water Bath

(ii) Thermometer

(iii) Heater

(iv) Marshall Test Apparatus

The procedure followed when conducting this test was:

1. Three (3) bituminous samples with different filler compositions were prepared.
2. Marshall properties of each sample were obtained.
3. Each sample was immersed in water for 24 hours at 60°C.
4. Marshall properties of each sample after immersion were obtained.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Bitumen Testing

4.1.1 Standard Penetration Test

Table 4.1: Results of Standard Penetration Test

Temperature: 25°C		Load: 100 g	Time: 5 seconds	
Sample	Determination 1	Determination 2	Determination 3	Mean
A	88.00	86.00	86.00	86.67
B	85.00	85.00	85.00	85.00

Table 4.1 presents the data obtained from the Standard Penetration Test conducted on two Grade 80/100 Bitumen samples. Three points were selected on each sample, and tests were conducted on both samples for each point. The points are located not less than 10 mm from the side of the container and not less than 10 mm apart. The selection of the points in this manner was to ensure accuracy of the results obtained.

Results have shown that the penetration values for samples A and B are 86.67 and 85.00 respectively, which are greater than 80, and do not exceed 100. The differences between the determinations did not exceed four (BS 2000: Part 49:1983 "Penetration of Bituminous Materials"). In conclusion, the Grade 80/100 Bitumen passed the test and can be used throughout this study.

4.1.2 Ring-and-Ball Softening Point Test

Table 4.2: Results of Ring-and-Ball Softening Point Test

Sample	Ball 1 (°C)	Ball 2 (°C)	Mean (°C)
A	49.0	48.7	48.9
B	48.2	47.9	48.1

Table 4.2 shows the results of the Ring-and-Ball Softening Point Test conducted on two Grade 80/100 Bitumen samples. Data obtained shows that the softening point values for samples A and B are 48.9 °C and 48.1 °C respectively, which are more than 45°C and less than 52°C. The differences between the temperatures of ball 1 and ball 2 for both samples did not exceed 1°C. With that, it can be concluded that the Grade 80 bitumen can be used throughout this research.

4.2 Aggregate Testing

4.2.1 Specific Gravity and Water Absorption Test

1. Fine Aggregates

Table 4.3: Results of Specific Gravity Test for Fine Aggregates

			Test	
			1	2
Mass of saturated surface-dry sample in air	A	(g)	488	490
Mass of vessel containing sample and filled with water	B	(g)	1857	1851
Mass of vessel filled with water only	C	(g)	1555	1546
Mass of oven-dry sample in air	D	(g)	481	482

		Test		Average
		1	2	
Particle density on an oven-dried basis	$\frac{D}{A-(B-C)}$	2.59	2.61	2.60

Particle density on a saturated and surface-dried basis	$\frac{A}{A-(B-C)}$	2.62	2.65	2.64
Apparent particle density	$\frac{D}{D-(B-C)}$	2.69	2.72	2.71
Water absorption (% of dry mass)	$\frac{100(A-D)}{D}$	1.46%	1.66%	1.56%

2. Coarse Aggregates

Table 4.4: Results of Specific Gravity Test for Coarse Aggregates

			Test	
			1	2
Mass of saturated surface-dry sample in air	*A*	(g)	988	995
Mass of vessel containing sample and filled with water	*B*	(g)	2155	2198
Mass of vessel filled with water only	*C*	(g)	1489	1535
Mass of oven-dry sample in air	*D*	(g)	976	989

		Test		Average
		1	2	
Particle density on an oven-dried basis	$\frac{D}{A-(B-C)}$	3.03	2.98	3.01
Particle density on a saturated and surface-dried basis	$\frac{A}{A-(B-C)}$	3.07	3.00	3.04
Apparent particle density	$\frac{D}{D-(B-C)}$	3.15	3.03	3.09

Water absorption (% of dry mass)	$\frac{100(A-D)}{D}$	1.23%	0.61%	0.92%

The data obtained shows that the water absorption values for both fine and coarse aggregates are lower than 2%.

4.3 Marshall Properties Test

4.3.1 Preparation of Untreated Samples with Different Binder Contents

Five samples were prepared with the following specifications:

1. Mixture Weight: 1200 g
2. Aggregate Type and Grading: Well-Graded Granite

Table 4.5: Well-Graded Granite Aggregate Mix Specification [10]

Aggregate Type	*Percent by Weight (%)*
Coarse Aggregate	70
Fine Aggregate	26
Filler	4

Sieve shaking was done to separate the different aggregate sizes. The correct gradation was obtained by weighing the aggregates retained on each sieve before putting it into the mix. The mix designation used for this study is the ACW14 as described in the JKR Manual. [10]

Table 4.6: Well Gradation Limits for Asphaltic Concrete of Type ACW14 [10]

B.S. Sieve Size	*Percent Passing By Weight (%)*
37.5 mm	-
28.0 mm	-
20.0 mm	100
14.0 mm	80 – 95

10.0 mm	68 – 90
5.0 mm	52 – 72
3.35 mm	45 – 62
1.18 mm	30 – 45
425 μm	17 – 30
150 μm	7 – 16
75 μm	4 - 10

3. Bitumen Grade: 80/100
4. Filler: Ordinary Portland Cement

The binder contents for each sample are 4.5%, 5.0%, 5.5%, 6.0% and 6.5% respectively. The Marshall Properties Test is conducted to obtain the values of the following Marshall properties for each sample:

1. Density
2. Stability
3. Voids Filled with Bitumen (VFB)
4. Voids in Total Mix (VTM)
5. Flow
6. Stiffness

The Density, Stability, VFB and VTM were obtained for the determination of the Optimum Binder Content (OBC), whereas the Flow and Stiffness were obtained for the verification of the OBC.

4.3.2 Determination of Optimum Binder Content (OBC)

Table 4.7: Density of Untreated Samples at Various Binder Contents

Binder Content (%)	*Density (g/cm³)*
4.5	2.346
5.0	2.342
5.5	2.355
6.0	2.350
6.5	2.347

Figure 4.1: Graph of Density versus Binder Content

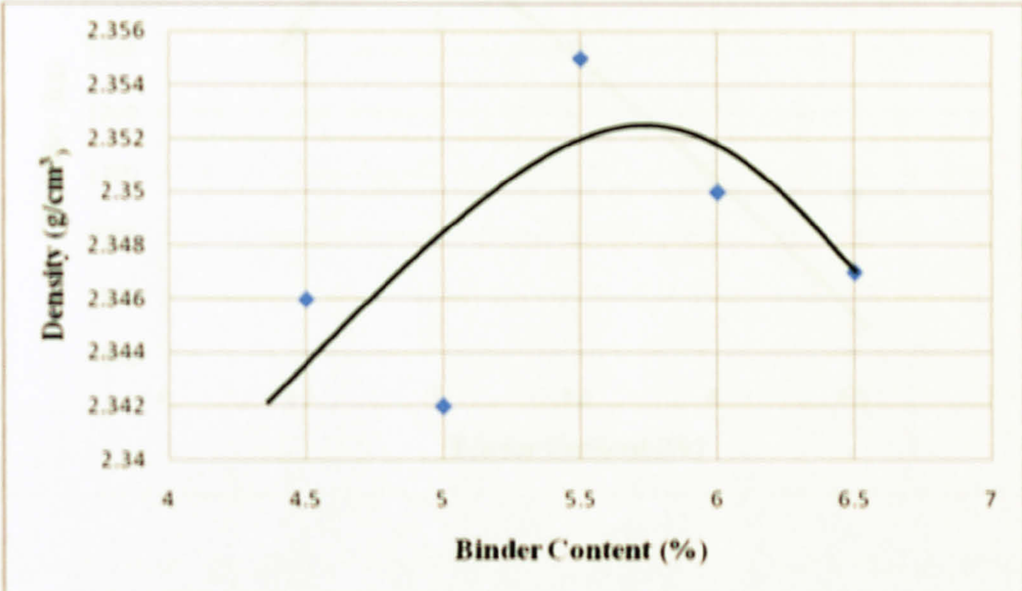

Table 4.7 shows the density of each sample obtained by conducting Marshall Testing. The correlation between density and binder content is illustrated in Figure 4.1. Starting from 4.5% binder content, the density increases until it reaches a peak value of 2.353 g/cm³ at 5.75% binder content, before it decreases.

Table 4.8: Stability of Untreated Samples at Various Binder Contents

Binder Content (%)	*Stability (kg)*
4.5	1329
5.0	1347
5.5	1310
6.0	1076
6.5	1063

Figure 4.2: Graph of Stability versus Binder Content

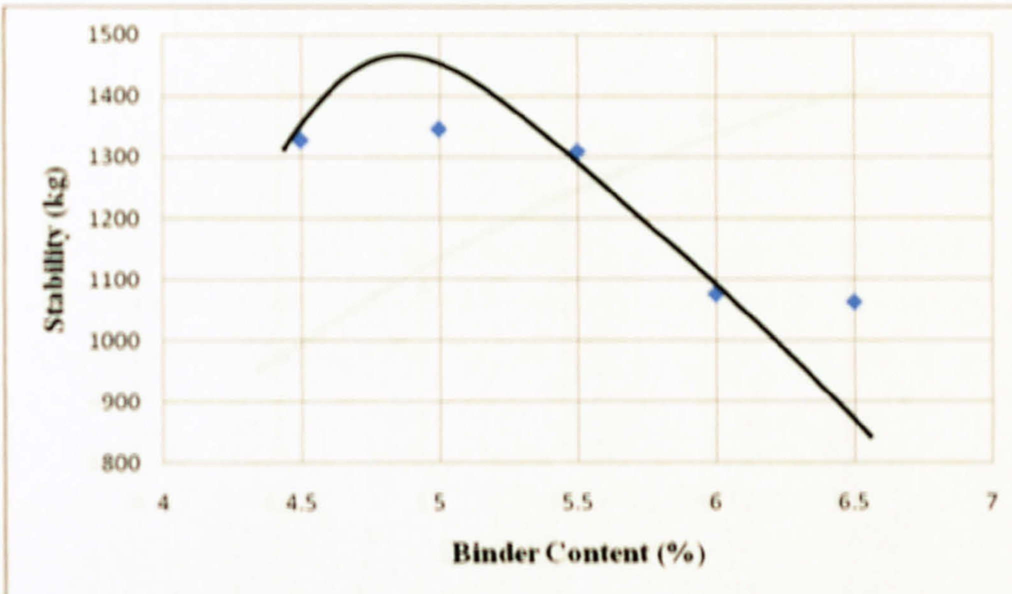

Table 4.8 shows the stability of each sample. The correlation between stability and binder content is illustrated in Figure 4.2. Starting from 4.5% binder content, the stability increases until it reaches a peak value of 1490 kg at 4.85% binder content, before it decreases.

Table 4.9: VFB of Untreated Samples at Various Binder Contents

Binder Content (%)	*VFB (%)*
4.5	68.6
5.0	74.2
5.5	79.8
6.0	88.1
6.5	90.3

Figure 4.3: Graph of VFB versus Binder Content

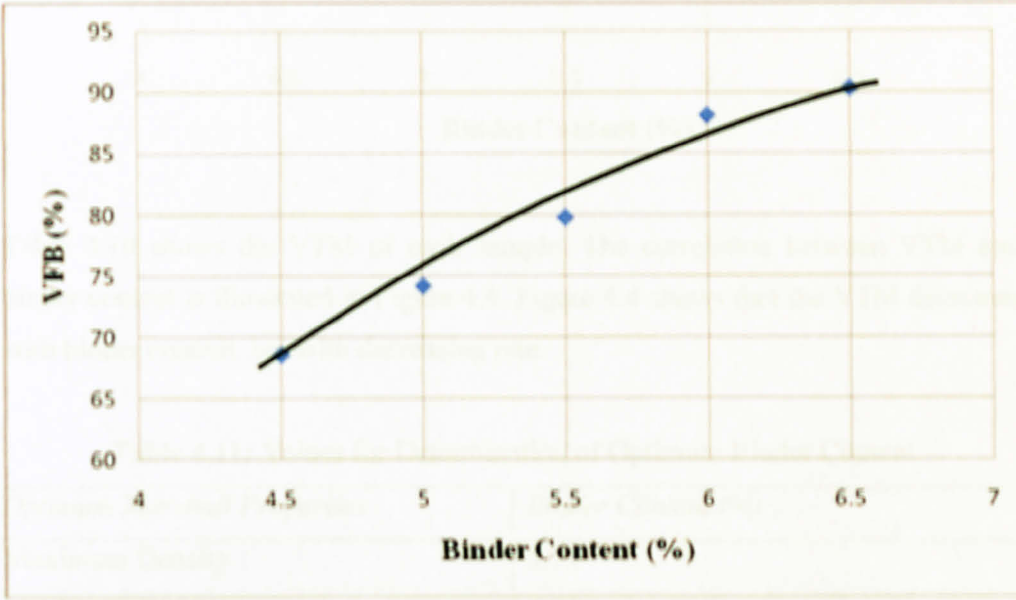

Table 4.9 shows the VFB of each sample. The correlation between VFB and binder content is illustrated in Figure 4.3. Figure 4.3 shows that the VFB increases with binder content, but with decreasing rate.

Table 4.10: VTM of Untreated Samples at Various Binder Contents

Binder Content (%)	*VTM (%)*
4.5	4.7
5.0	3.8
5.5	2.8
6.0	1.7
6.5	1.6

Figure 4.4: Graph of VTM versus Binder Content

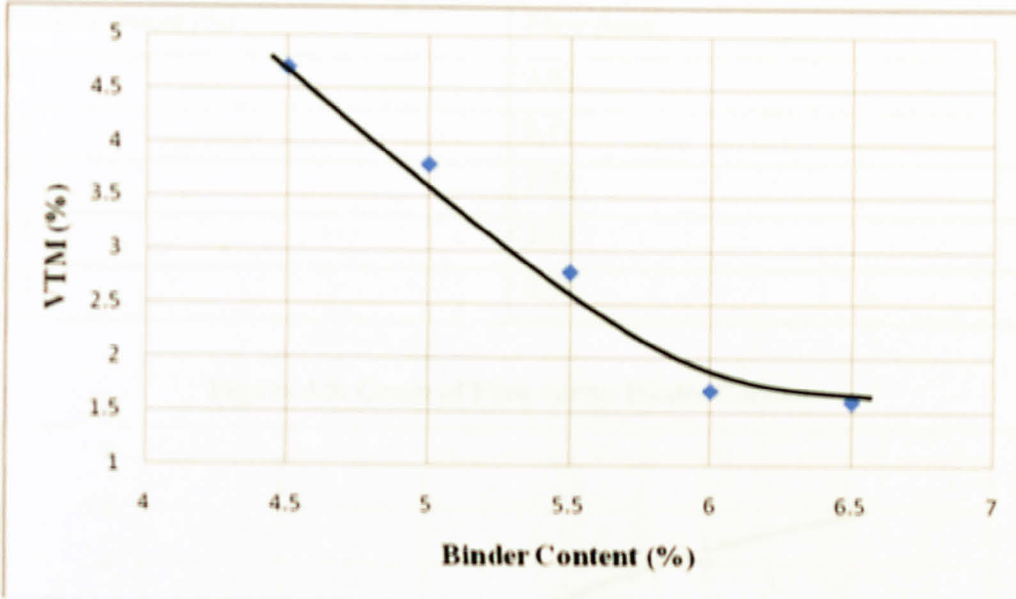

Table 4.10 shows the VTM of each sample. The correlation between VTM and binder content is illustrated in Figure 4.4. Figure 4.4 shows that the VTM decreases with binder content, but with decreasing rate.

Table 4.11: Values for Determination of Optimum Binder Content

Optimum Marshall Properties	*Binder Content (%)*
Maximum Density	5.75
Maximum Stability	4.85
Median VFB	5.25
Median VTM	5.00

Table 4.11 presents the values of binder content obtained at maximum density, maximum stability, median VFB and median VTM. The OBC is determined as the following:

$$OBC = \frac{5.75+4.85+5.25+5.00}{4} = 5.21\%$$

Table 4.12: Flow of Untreated Samples at Various Binder Contents

Binder Content (%)	*Flow (mm)*
4.5	0.92
5.0	2.11
5.5	2.35
6.0	3.02
6.5	3.56

Figure 4.5: Graph of Flow versus Binder Content

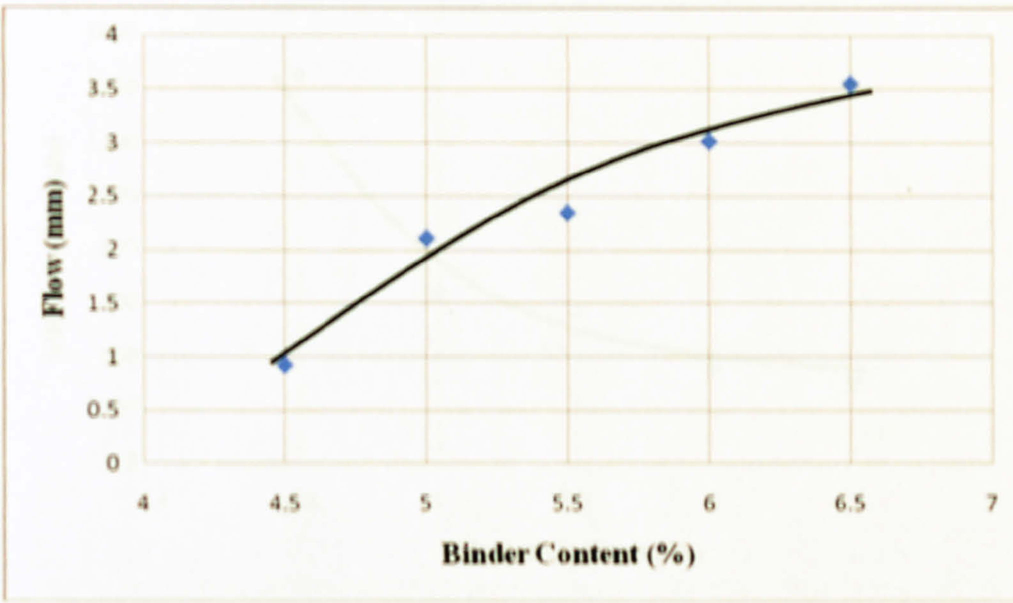

Table 4.12 shows the flow of each sample. The correlation between flow and binder content is illustrated in Figure 4.5. Figure 4.5 shows that flow increases with binder content, but with decreasing rate.

Table 4.13: Stiffness of Untreated Samples at Various Binder Contents

Binder Content (%)	*Stiffness (kg/mm)*
4.5	1445
5.0	638
5.5	557
6.0	356
6.5	299

Figure 4.6: Graph of Stiffness versus Binder Content

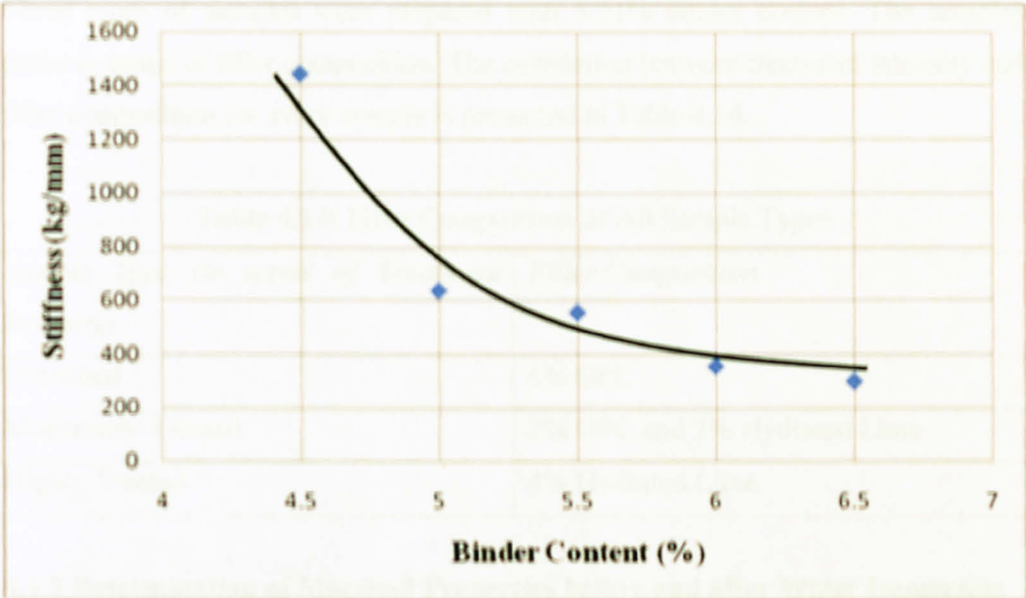

Table 4.13 shows the stiffness of each sample. The correlation between stiffness and binder content is illustrated in Figure 4.6. Figure 4.6 show that stiffness decreases with binder content, but with decreasing rate.

4.3.3 Preparation of Untreated Sample at Optimum Binder Content for Verification

An untreated sample with the same filler content and aggregate gradation is prepared, but this time, the binder content is at its optimum value, which is 5.21%.

For verification, Marshall Testing is conducted on the sample to obtain its Flow and Stiffness. These values are then compared with the values of Flow and Stiffness at 5.21% binder content as plotted on Figure 4.5 and Figure 4.6. The values matched and the sample passed the verification process.

4.4 Moisture Susceptibility Test

4.4.1 Preparation of Treated Samples

Three types of samples were prepared with 5.21% binder content. The samples differ in terms of filler composition. The correlation between treatment intensity and filler composition for every sample is presented in Table 4.14.

Table 4.14: Filler Composition of All Sample Types

Sample Type (in terms of Treatment Intensity)	*Filler Composition*
Untreated	4% OPC
Moderately Treated	2% OPC and 2% Hydrated Lime
Highly Treated	4% Hydrated Lime

4.4.2 Determination of Marshall Properties before and after Water Immersion

Marshall Testing was conducted on all samples before and after immersing them in water at 60°C for 24 hours. The results are as the following:

Table 4.15: Marshall Properties of Samples before Water Immersion

Marshall Properties	4% OPC	2% OPC and 2% HL	4% HL
Stability (kg)	1348	1370	1398
Flow (mm)	2.17	2.17	2.14
Stiffness (kg/mm)	621	631	653

Table 4.16: Marshall Properties of Samples after Water Immersion

Marshall Properties	4% OPC	2% OPC and 2% HL	4% HL
Stability (kg)	1320	1342	1375
Flow (mm)	2.27	2.26	2.22
Stiffness (kg/mm)	581	594	619

Table 4.15 and Table 4.16 show that water immersion decreases the Stability, increases the Flow and decreases the Stiffness of each sample.

4.4.3 Determination of Immersion Index

Immersion Index is a parameter that indicates the amount of fluctuation in the values of Marshall Properties due to water immersion. Immersion Index is expressed in percentage.

Immersion Index for sample containing 4% OPC:

$$\text{Stability} = \frac{1348 - 1320}{1348} \times 100\% = 2.08\%$$

$$\text{Flow} = \frac{2.27 - 2.17}{2.17} \times 100\% = 4.61\%$$

$$\text{Stiffness} = \frac{621 - 581}{621} \times 100\% = 6.44\%$$

Immersion Index for sample containing 2% OPC and 2% Hydrated Lime:

$$\text{Stability} = \frac{1370 - 1342}{1370} \times 100\% = 2.04\%$$

$$\text{Flow} = \frac{2.26 - 2.17}{2.17} \times 100\% = 4.22\%$$

$$\text{Stiffness} = \frac{631 - 594}{631} \times 100\% = 5.86\%$$

Immersion Index for sample containing 4% Hydrated Lime:

$$\text{Stability} = \frac{1398 - 1375}{1398} \times 100\% = 1.65\%$$

$$\text{Flow} = \frac{2.22 - 2.14}{2.14} \times 100\% = 3.91\%$$

$$\text{Stiffness} = \frac{653 - 619}{653} \times 100\% = 5.21\%$$

Table 4.17: Immersion Index

Marshall Properties	Immersion Index (%)		
	4% OPC	2% OPC and 2% HL	4% HL
Stability	2.08	2.04	1.65
Flow	4.61	4.22	3.91
Stiffness	6.44	5.86	5.21

Figure 4.7: Graph of Immersion Index versus Filler Composition

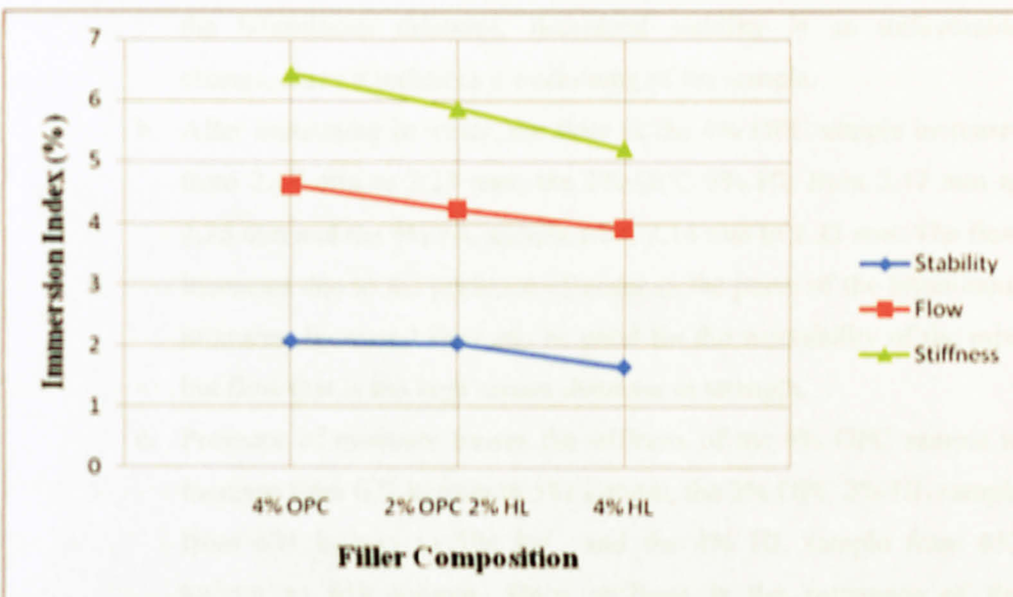

Figure 4.7 shows that as the content of Hydrated Lime increases in the filler composition, the Immersion Index decreases. Data presented proves that Hydrated Lime decreases effects of water on Marshall Properties better than Ordinary Portland Cement.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The laboratory tests conducted have resulted in the following conclusions:

i. Water affects the bituminous mixtures in the following manner:

   a. Intrusion of water into the bituminous mixture decreases its stability of the 4% OPC sample from 1348 kg to 1320 kg, the 2% OPC 2% HL sample from 1370 kg to 1342 kg and the 4% HL sample from 1398 kg to 1375 kg. Since stability is the load carrying capacity of the bituminous mixtures, decreased stability is an unfavorable change, since it indicates a weakening of the sample.

   b. After immersing in water, the flow of the 4% OPC sample increases from 2.17 mm to 2.27 mm, the 2% OPC 2% HL from 2.17 mm to 2.26 mm and the 4% HL sample from 2.14 mm to 2.22 mm. The flow increases due to the presence of water in the pores of the bituminous mixtures. Increased flow can be good for the workability of the mix, but flow that is too high causes decrease in strength.

   c. Presence of moisture causes the stiffness of the 4% OPC sample to increase from 621 kg/mm to 581 kg/mm, the 2% OPC 2% HL sample from 631 kg/mm to 594 kg/,, and the 4% HL sample from 653 kg/mm to 619 kg/mm. Since stiffness is the resistance of the bituminous mixture to deformation, decreased stiffness indicates that the mixture is more susceptible to deformation. This is an unfavorable change in the Marshall property.

   d. The nation's roads and highway are exposed to water frequently due to the climatic and environmental conditions. Intrusion of water into the pavement material will cause the Marshall properties of the bituminous mixture to fluctuate unfavorably, hence, weakening the pavements, and making it more susceptible to deformation and distresses. In conclusion, this research must be expanded, to include testing of all the various methods of modifying binders, aggregate treatment, addition of anti-stripping agents and determining filler composition, to come out with methods of increasing the resistance of bituminous mixtures towards the effects of water.

ii. The Immersion Index obtained for stability, flow and stiffness decreases with the increase in the content of Hydrated Lime, and the decrease in the content of Ordinary Portland Cement. The Immersion Index for stability decreases from 2.08% for the 4% OPC sample, to 2.04% for the 2% OPC 2% HL sample and to 1.65% for the 4% HL sample. For flow, it also decreases from 4.61% for the 4% OPC sample, to 4.22% for the 2% OPC 2% HL sample and to 3.91% for the 4% HL sample. For stiffness, the Immersion Index also decreases from 6.44% for the 4% OPC sample, to 5.86% for the 2% OPC 2% HL sample and to 5.21% for the 4% HL sample. The Immersion Index indicates the amount of fluctuation of the Marshall property due to water immersion. The decrease in Immersion Index for each Marshall property obtained indicates that Hydrated Lime increases the resistance of the bituminous mixtures towards the effects of water better than Ordinary Portland Cement.

5.2 Recommendations

This study can be expanded to achieve more advanced research results by increasing the scope of study in the following manner:

1. Explore the various treatment methods available such as lime-slurry treatment of the aggregates, bitumen pre-coating of the aggregates, careful selection of the aggregates using special mineral fillers or not allowing hydrophilic aggregates, washing or blending of aggregates, addition of chemical anti-stripping agents and modification of the bituminous binder.

2. Instead of studying the effects of water only, the scope can be expanded by including the study of other liquids that are in contact with pavements frequently, such as petrol, acid rain and etc.

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